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Technical Report No. 99

Data Assimilation Within The Forecasting Ocean Atmosphere Model (FOAM)

by

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Abstract - **FOAM, the Forecasting Ocean Atmosphere Model, is a system designed to produce analyses and short-range forecasts for the deep ocean. At the heart of FOAM is a standard numerical model of the ocean. The system uses the "Analysis Correction" scheme to analyse observations. The main advantages of this scheme are that it is relatively inexpensive (especially when compared with full variational methods), and that it results in balanced fields for the model. Tests of the data assimilation scheme have been run, initially for a version of the model covering the Atlantic and Arctic Oceans. For these, the model used observations received in real time at the Met. Office from the Global Telecommunications System of the World Meteorological Organisation.**

I. INTRODUCTION

There are several stages in producing a forecast of the state of the ocean. First, the present conditions must be determined: the observations must be interpreted; their accuracy must be assessed and they must be merged with earlier estimates of the ocean state (known as background fields) to produce a consistent analysis of the state of the ocean. Following this it is possible to produce a forecast; increasingly numerical models are being used to help with this. Only when the forecast of the basic oceanographic conditions has been made is it possible to produce forecasts of those quantities of interest to the end user.

This paper describes a system that is being developed to receive observations in real time and use them to influence the evolution of a numerical model, a process called data assimilation.

The layout of this paper follows the steps in running an operational system. First, the observations are discussed; these are the starting point for the operational system. Next the numerical model is described; this provides the background fields that would be the estimate of the state of the ocean if there were no new observations available. The next section discusses the data assimilation scheme that combines observations with the evolving model simulation. Experiences with testing the system are then discussed. Finally, the results are summarised and future plans are suggested.

II. OBSERVATIONS

FOAM, the Forecasting Ocean Atmosphere Model, is designed to use observations that are reported in real time. These are transmitted through the Global Telecommunications System of the World Meteorological Organisation and placed in the main database at the Meteorological Office.

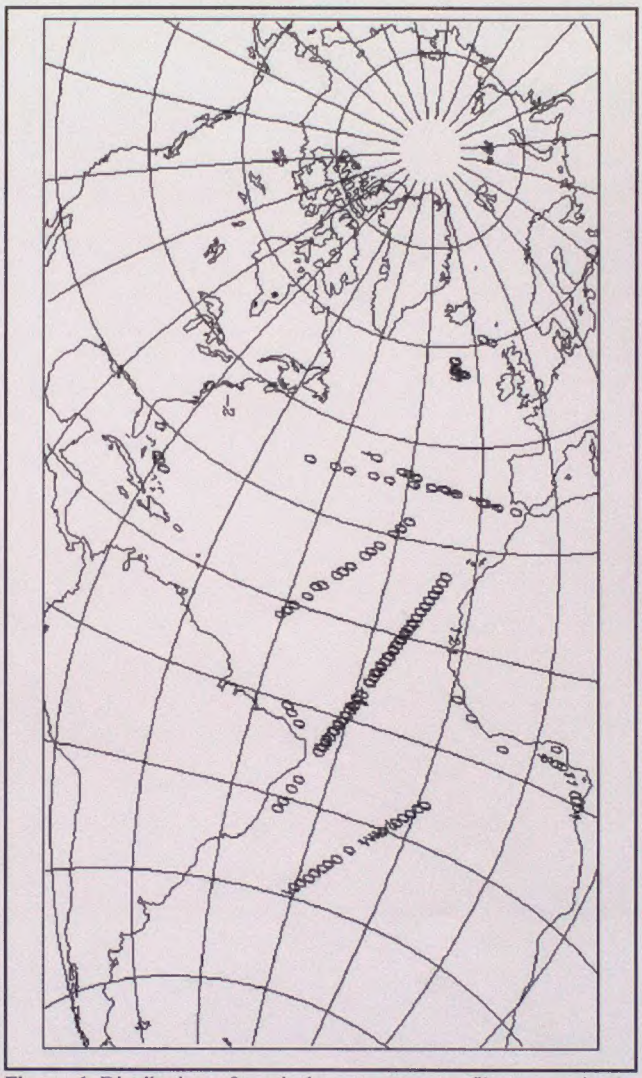

Figure 1 Distribution of vertical temperature profile reports in the Atlantic for the second week of April 1993.

Conventional observations offer valuable information about the ocean interior. Temperature profiles from eXpendable BathyThermographs (XBTs, reported as BATHY messages) and Conductivity Temperature Depth (CTD, reported as TESAC messages) instruments were the first to be included in the system. These observations are the only direct source of information on the vertical structure of the ocean. Fig. 1

shows that they are sparse. Observations from these instruments can contain errors from various sources: the instrument itself may fail to work correctly (e.g. [1]), transcription errors might occur in preparing the observation for transmission, and the calibration of the instrument may be inappropriate (e.g. [2]). The FOAM system attempts to identify these errors. In the version used for these preliminary tests the observations were compared with climatology and those that differed by more than 4°C were rejected; if more than half the data points in a profile were rejected the whole profile was discarded.

The Met. Office receives about 2500 ship observations of sea surface temperature each day. Although these are more plentiful, and more widely distributed, than the measurements of temperature profiles there are still large regions that are not sampled. These observations are used to produce analyses of sea surface temperature for the operational weather forecast system [3]; FOAM uses the quality control decisions from the weather forecast system for these observations.

Satellite observations of sea surface temperature cover a much larger area than the other observation types, although infra-red measurements are only available where there is no cloud. Errors in satellite observations have different characteristics from other measurements. They are often biased over large areas; e.g. because of the "skin effect" in which the top millimetre of the sea has a different temperature from the bulk of the water, or atmospheric aerosol between the satellite and the sea surface that is not taken account of in the methods of deriving sea surface temperature. Quality control for these observations is also taken from the weather forecast suite.

III. NUMERICAL MODEL

A. Ocean model

At the heart of the FOAM system is a three dimensional model of the ocean general circulation. It is derived from that developed by the Geophysical Fluid Dynamics Laboratory ([4], [5]). In addition to the basic schemes, the model represents diffusion along isopycnals [6], mixed layer processes following [7], penetration of solar radiation below the first ocean layer and sea ice [8].

Initial experiments, described in this paper, used a grid covering the Atlantic and Arctic Oceans. The pole of the rotated regular latitude-longitude grid was at 17°N 56°E so that the equator of the grid lay along the centre of the Atlantic. This gave a grid that was more evenly spaced than a conventional grid. The horizontal resolution of the model was 1° in each direction and the model had 20 layers that ranged in thickness from 10 m near the surface to 600 m at the bottom of the ocean. The coastline and topography in the model were realistic. The model used a half hour time step.

The ocean circulation is driven by fluxes of heat, fresh water, and momentum through the ocean surface.

Ocean models have used several methods to derive the heat flux. Perhaps the simplest is to follow [9] and relax the surface temperature in the ocean model towards a prescribed value, often taken to be the observed climatological sea surface temperature. A variation of this method is to use climatological estimates of the surface fluxes and to add a relaxation towards the sea surface temperature climatology as well (this was what [9] intended). FOAM substitutes surface heat fluxes calculated by a weather forecast model for the climatological estimates of the heat flux; for development, and when the fluxes from the weather forecast models are not available for any reason, FOAM can use climatological estimates of the fluxes [10].

Fresh water fluxes are difficult to observe over the oceans. FOAM uses values calculated by the weather forecast model or climatological estimates produced by combining [10] and [11].

FOAM uses wind stresses from the weather forecast model or from the climatology of [12].

B. Weather forecast model

Weather forecast systems run at the Met. Office several times each day. The model used to drive the FOAM system is the global model. This produces analyses and five day forecasts twice a day. This model and its data assimilation system are described by [13]. It has horizontal resolution of 1.25° longitude by 0.833° latitude and has 19 unequally spaced levels in the vertical. Six hour average surface fluxes are produced by the model throughout its run. Fluxes for the first twelve hours of the forecast were used in the experiments described here; this is because the "analysed" estimates of precipitation are appreciably less than those produced by the model during its forecast ([14]).

The FOAM system uses unmodified NWP fluxes, the only processing being to interpolate the fluxes onto the FOAM grid.

IV. DATA ASSIMILATION

A. Aim of data assimilation

Data assimilation aims to produce a consistent estimate of the state of the physical system. Atmosphere and ocean assimilation schemes seek to obtain a balance between the observations (these have errors) and a previous estimate of the state of the system (usually a forecast), so as to produce an initial state that will allow the model forecast to evolve smoothly from it. Often data analysis (merging the observations with the previous estimate) is performed separately from an "initialisation" step that imposes dynamical consistency on the analysed fields. Other schemes impose the equations of the numerical model as a constraint on the time evolution of the analysed fields ("4D variational technique"). A review of techniques used for atmospheric data assimilation may be found in [15].

FOAM uses a variant of the "Analysis Correction" scheme of [16]. This is an inexpensive iterative method for analysing the data. Iterations of the analysis are interleaved with time steps of the numerical model. The advantage of this method is that the model is able to adjust to the analysis of the observations because the change imposed by the analysis scheme at any time step is small. Fig. 2 illustrates the AC scheme.

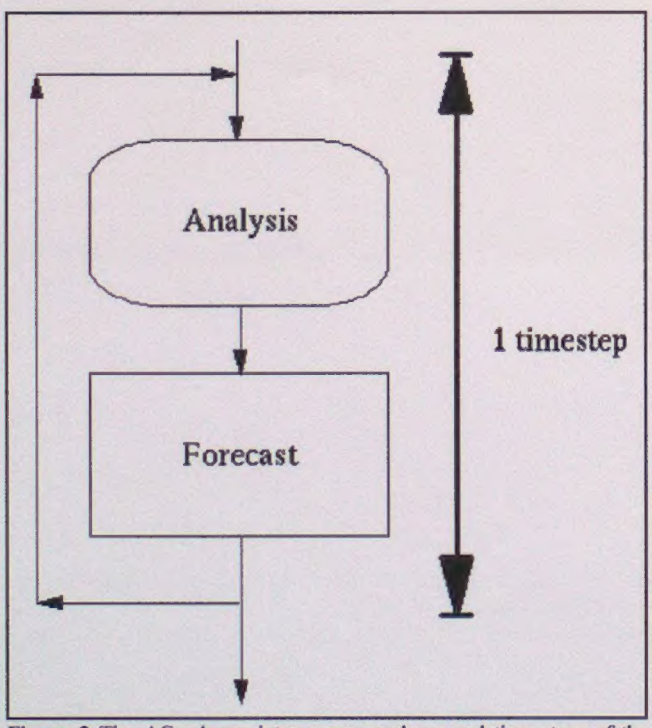

Figure 2 The AC scheme intersperses analyses and time steps of the model.

B. Conventional observations

The principal features of conventional observations, XBT CTD and ship surface temperature reports, are that they are sparse in time and space, and that errors in observations at one portion are generally independent of those surrounding them.

Analysis of these observations takes place in four stages. First, the model "background" value for the observed quantity (e.g. temperature) is interpolated to the observation points. The differences between these estimated values and the observed ones are then calculated. The third step is to interpolate the differences back to the grid points of the model. Finally, a portion of these differences is added to the background fields for the model to use in its next time step.

The subtleties of data assimilation, and the need for such a tortuous method for deriving increments to the background fields, are hidden in the term "interpolate" [17].

The factors taken into account by the interpolation method are best described by example.

Consider interpolating from the background value to an observed temperature. In general the observation will not be at the same depth or horizontal position as the model values. Spatial interpolation is needed. A simple method is to use linear interpolation (because the model values are on a regular grid). Once a value is known at the observation point, it must be converted to the correct physical variable (observations are of temperature, the model uses potential temperature; in practice, FOAM converts observations to potential temperature). In the mathematical formulation of the scheme, this interpolation is written as a single "transformation function", and each observed variable might have a different transformation function.

Interpolating from the observation positions to the position of background values is also represented by a transformation function. Continuing the example, the difference between observed and background temperature is converted back to potential temperature (not needed in FOAM), and this must then be interpolated in space. The spatial transformation this time must take account not only of the spatial correlation in errors in the background field, but also those in the observations.

Once the analysed difference between the observations and the background values has been found, a proportion of it is added to the background value. With appropriate choices of transfer functions and proportion of the difference to add to the background field it is technically possible to make the results from this scheme the same as from Optimal Inte-

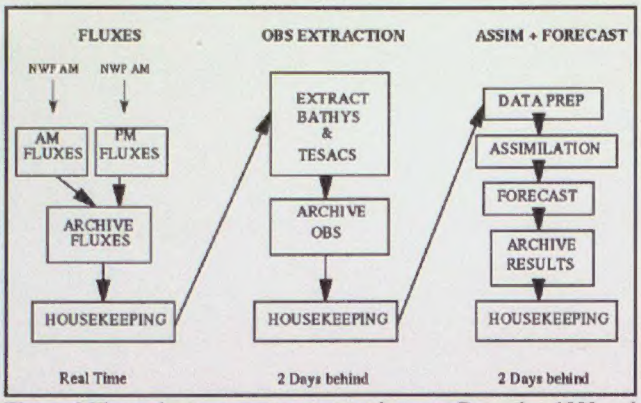

Figure 3 The main components were run between December 1993 and February 1994 two days behind real time to use observations.

rpolation [15] if the analysis is iterated.

C. Satellite sea surface temperature

Satellite measurements of sea surface temperature differ from conventional observations in two ways. First, there are far more satellite observations in most regions. Second, errors in conventional observations are usually uncorrelated, whereas errors in satellite observations are often similar over large areas as a result of measurement bias.

To reduce the cost of assimilating the large quantity of satellite sea surface temperature data into the model, a slightly different, cheaper way of spatial interpolation from observations to the background field is employed. This interpolation method is known as the "Filtered Increments" scheme, and spreads the difference between the observation and the background field (i.e. the increment) to the grid by means of a recursive filter. The method is simply an alternative to the spatial transformation function used for conventional observations, and similarly takes account of the spatial correlation of background and observation errors.

As before, background values are interpolated to observation positions and the differences between the observed and background values are calculated. The interpolation process is the reversed to find the values of the increments at model points. A recursive filter is then applied to the increments. This filter sweeps along each grid row and column of the model, taking a weighted average of the value at a grid point and the previous grid point. Each complete pass of the filter consists of four sweeps: left to right, right to left, bottom to top, and top to bottom. Two complete passes of the filter spread the observation increments in an equivalent way to the spatial transformation used for conventional observations.

One method for removing the bias in satellite observations uses the recursive filter. By repeated application of the filter, the increment field is smoothed out to such an extent that only the large space-scale variations remain. The resulting field is effectively the bias, and by interpolating this field back to the satellite observations and subtracting from the initial increments, unbiased estimates of the observation values are obtained.

Increments resulting from the application of the recursive filter are applied to the model background field in the same way as increments from conventional observations.

Sea surface temperatures were not assimilated in the experiments described in the next section.

V. RESULTS FROM TESTS OF THE SYSTEM

A. Near real time tests

During December 1993, January 1994 and February 1994, a preliminary version of the FOAM system was run in near real time. This was intended as a system test to demonstrate that the system could run unattended for an extended period.

Steps in the test system are illustrated in Fig. 3. Surface fluxes were archived for each main run of the weather forecast models as they were produced. These fluxes were then converted to the rotated grid of the FOAM model.

Two days later, observations of ocean temperature and salinity were extracted from the real time database of observations received on the Global Telecommunications System. Observations were not used if they differed from climatology by more than 4°C. Observations valid from five days before the analysis time to two days after it were used in each analysis.

The surface fluxes and observations were then used to drive a one day data assimilation run of the model. The results of this were passed to a one day forecast by the model, and were also used as the starting conditions for the

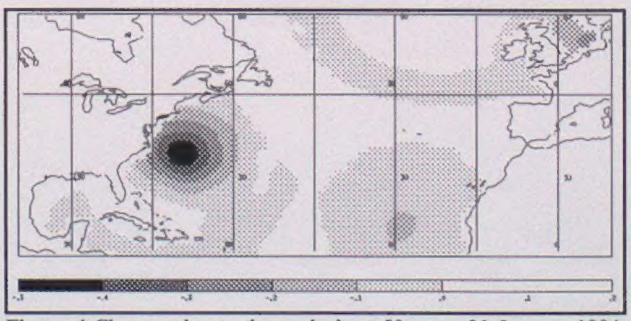

Figure 4 Changes due to the analysis at 50 m on 31 January 1994. Each shading band is 0.1°C wide. The darkest shading corresponds to -0.5°C.

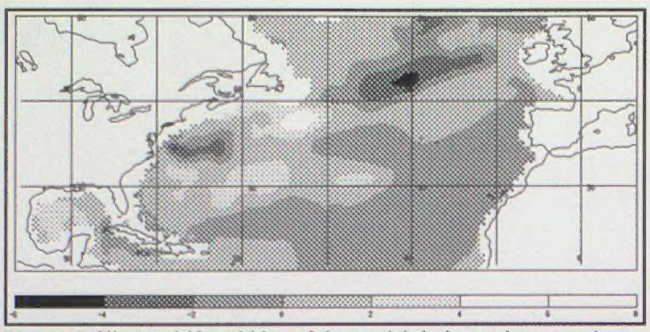

Figure 5 Climate drift at 300m of the model during a six year spin-up. Shading bands are 2°C wide.

next day's assimilation.

Fig. 4 shows the changes to the 50 m temperature field resulting from the assimilation of observations on 31 January 1994. It shows a typical distribution of the areas affected by observations.

In addition to checking that the computing aspects of the system worked as they were expected to, this test also highlighted areas that needed scientific development.

B. Case studies

During spring 1994, experiments were carried out with the FOAM analysis system, consisting of 21 separate integrations of the model. These were designed to test several aspects of the analysis, such as the impact of climate drift in the model, changes in the horizontal and vertical correlation scales. Integrations were performed for April, December and July to September, 1993.

The focus of the experiments was on the data assimilation scheme. Less attention was given to the numerical model; an illustration of this is that the South Atlantic was closed by an impenetrable wall in the model. As a consequence, there was substantial "climate drift" in the model before the trial integrations were started, so that the initial state was farther from the observations than was climatology. An immediate question that arose was thus: does the data assimilation scheme counteract the climate drift of the model. Comparing figs. 5 and 6 shows that the impact of data assimilation was to counteract the climate drift in the model.

Versions of the data assimilation system were run to investigate the impact on the vertically averaged flow of the treatment of observations below 600 m. Fig. 7 shows the vertically averaged streamfunction for the end of April after assimilating observations for a month using the original parameters for the FOAM assimilation. Fig. 8 shows the same field at the end of the spin-up (without data assimilation). It is clear that data assimilation has had two major impacts. First, as expected, the gradients (equivalent to the strength of currents) were increased near the Gulf Stream. Second, anomalous circulations developed south of Nova Scotia and off Iberia. The cause was traced to very large temperature increments at depth.

Two lessons were learned from these tests: the large model drift was unacceptable, and greater care was needed in using observations at large depths.

VI. SUMMARY AND PLANS

FOAM is designed to analyse the temperature of the ocean in near real time and to produce short forecasts from this initial state. It is based on a numerical model of the ocean. Observations are introduced into the system using the analysis correction technique.

Initial tests of the system have demonstrated that it is robust enough to allow scientific tests to be carried out.

Several case studies have been run to investigate the sensitivity of the analysis scheme to some of the assumptions built into it. Statistical analysis of the case studies showed that near the surface the analyses of the case studies were closer to observations than was climatology; at 300 m the analysis had similar accuracy to climatology, yet was a marked improvement on the initial state.

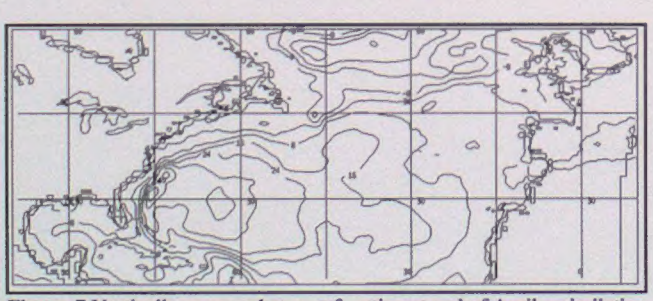

Figure 7 Vertically averaged stream function at end of April assimilation (contours at 8×10^6 m^3s^{-1}).

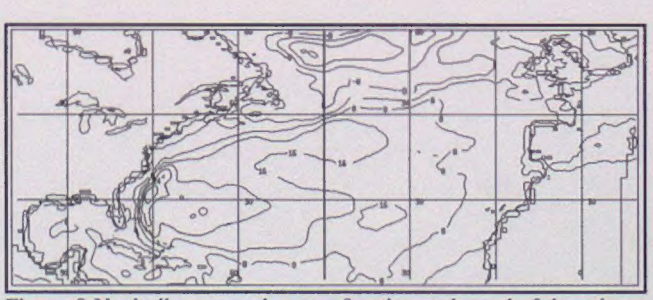

Figure 8 Vertically averaged stream function at the end of the spin-up (contours at 8×10^6 m^3s^{-1}).

Observations of deep temperatures are sparse, and the analysis scheme attempts to make full use of those that are available. One of the ways it does so is to extrapolate information from the observed profile deeper into the ocean; the case studies demonstrated that inappropriate extrapolation can have a major impact on the vertically averaged flow.

The next stage in developing the system is to change from a model covering the Atlantic and Arctic to a global one. This version of the model will assimilate surface temperatures from both ships and satellites. After further development of the model, assimilation scheme and quality control systems, the first operational implementation of FOAM is expected to be late in 1995, running several months behind real time to produce analyses for climate studies.

Longer term plans call for increased resolution for the numerical model so that fronts and eddies can be represented and the vertical structure of the upper ocean simulated more accurately. Higher resolution increases the need for observations. Altimeter observations can augment other observation types, and data assimilation techniques will be introduced into FOAM to allow these observations to be used. This presents major challenges.

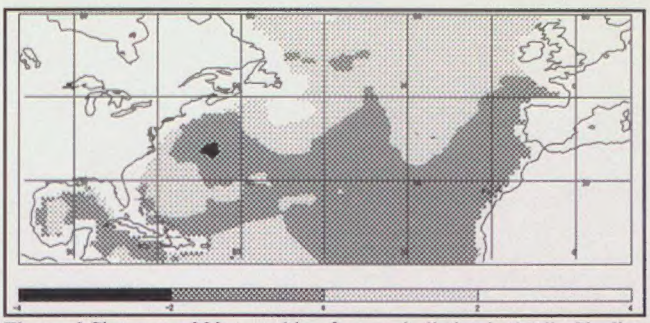

Figure 6 Changes at 300m resulting from assimilation in April. Shading is reversed from that in fig. 5, so assimilation has reversed the drift in areas where the shading is the same.

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